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SYNTHESIS OF A PLUME SIMULATOR FOR THE MX MISSILE

Dikewood Industries, Inc.
1100 Glendon Avenue
Los Angeles, California 90024

31 May 1978

Topical Report for Period 7 November 1977—31 May 1978

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Electromagnetic pulse
EMP
EMP Coupling
EMP Interaction
EMP Simulation
Missile Plume Modeling
Missile Plume Simulation
MX Missile

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A simulator for the exhaust plume of an MX missile is synthesized for use in the in-flight EMP hardness assessment of the missile in an EMP simulator. The synthesis is based on a set of results obtained in a numerical analysis of the interaction between the missile plume and an EMP which uses the Titan-III missile plume data scaled to the MX missile dimensions. It is found that, for this case, the plume simulator can be made entirely out of passive lumped LRC elements.

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I. INTRODUCTION

A ballistic missile in free flight emits continuously an enormous volume of exhaust gases from its engine nozzle. This exhaust is trailed behind the missile in the form of a gaseous plume. Within the earth's atmosphere the visible part of the plume has the appearance of a long, luminous column extending beyond the nozzle to a length of several times that of the missile.

The plume contains a high concentration of ions and electrons. The presence of these charged particles in the missile's immediate environment can effectively alter the electromagnetic characteristics of the missile. For example, if the plumed missile were to be struck by the electromagnetic pulse (EMP) of a nuclear explosion, as illustrated in Fig. 1, the electric current and charge induced by the EMP on the missile skin would assume different values than if the plume were absent.

The interaction of the MX missile in free flight with an EMP has been analyzed with a theoretical model [1]. The model employed the Titan-III missile plume data at an altitude of 20 kilometers and scaled to the MX missile dimensions. The EMP waveform was assumed of the double-exponential type. The total induced current flowing up from the plume onto the missile at the nozzle during the EMP encounter was calculated. Fig. 2 shows one set of the results of the calculation. The nozzle current I_{noz} in the frequency domain is here plotted versus the frequency f for broadside EMP incidence. The incident electric field is taken to be polarized along the length of the missile, and at a strength of 1 volt per meter.

When the missile is tested for its in-flight EMP hardness in an EMP simulator such as ARES, it is necessary to make up for the absence of the plume at testing with a plume simulator. One method of plume simulation is illustrated in Fig. 3. The figure shows a missile standing upright in an EMP simulator and struck by the simulator field. If the simulator field is a good simulation of the EMP, then the state of affairs above the nozzle duplicates correctly that in the in-flight EMP encounter depicted in Fig. 1.

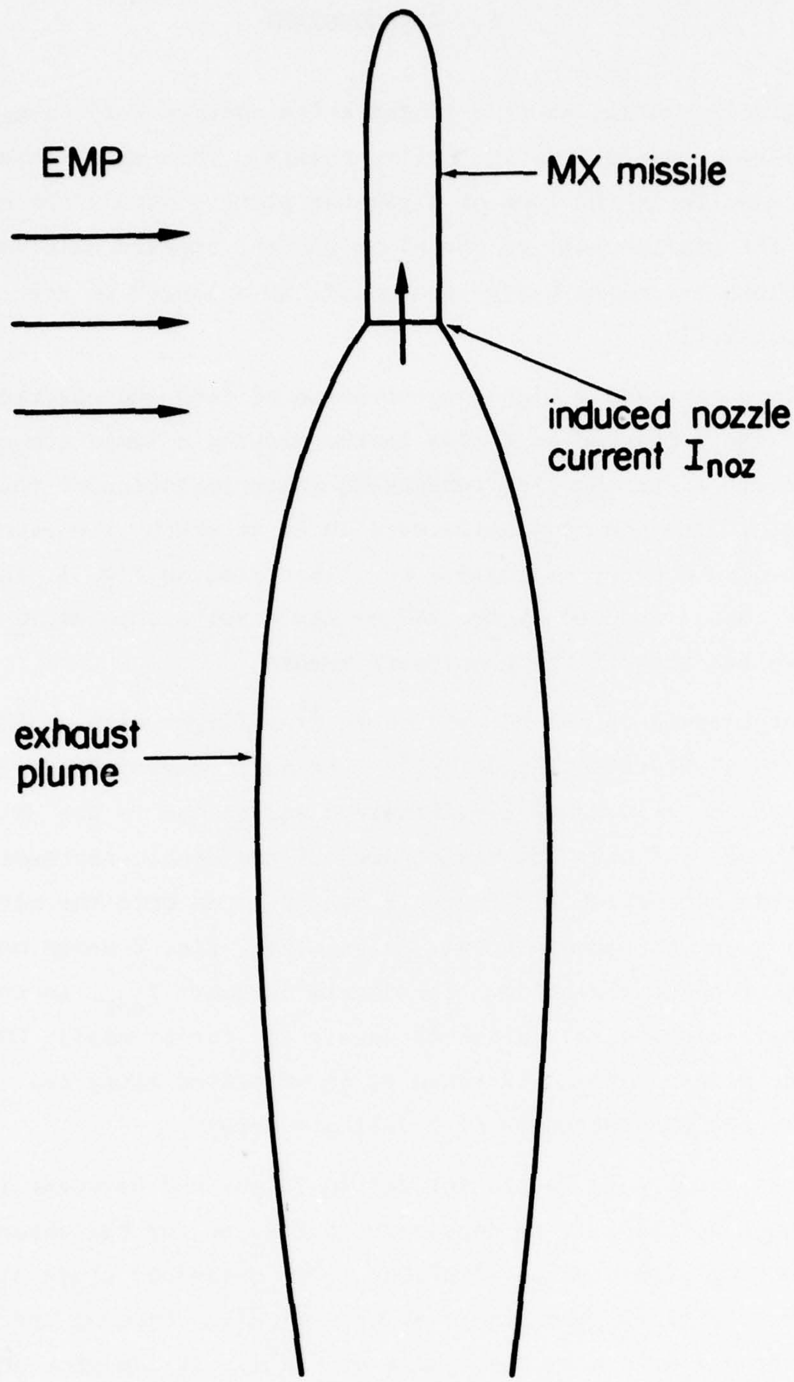

Fig. 1. Interaction of an EMP with an MX missile and its exhaust plume. The plume picks up an electric current and injects it onto the missile skin at the nozzle.

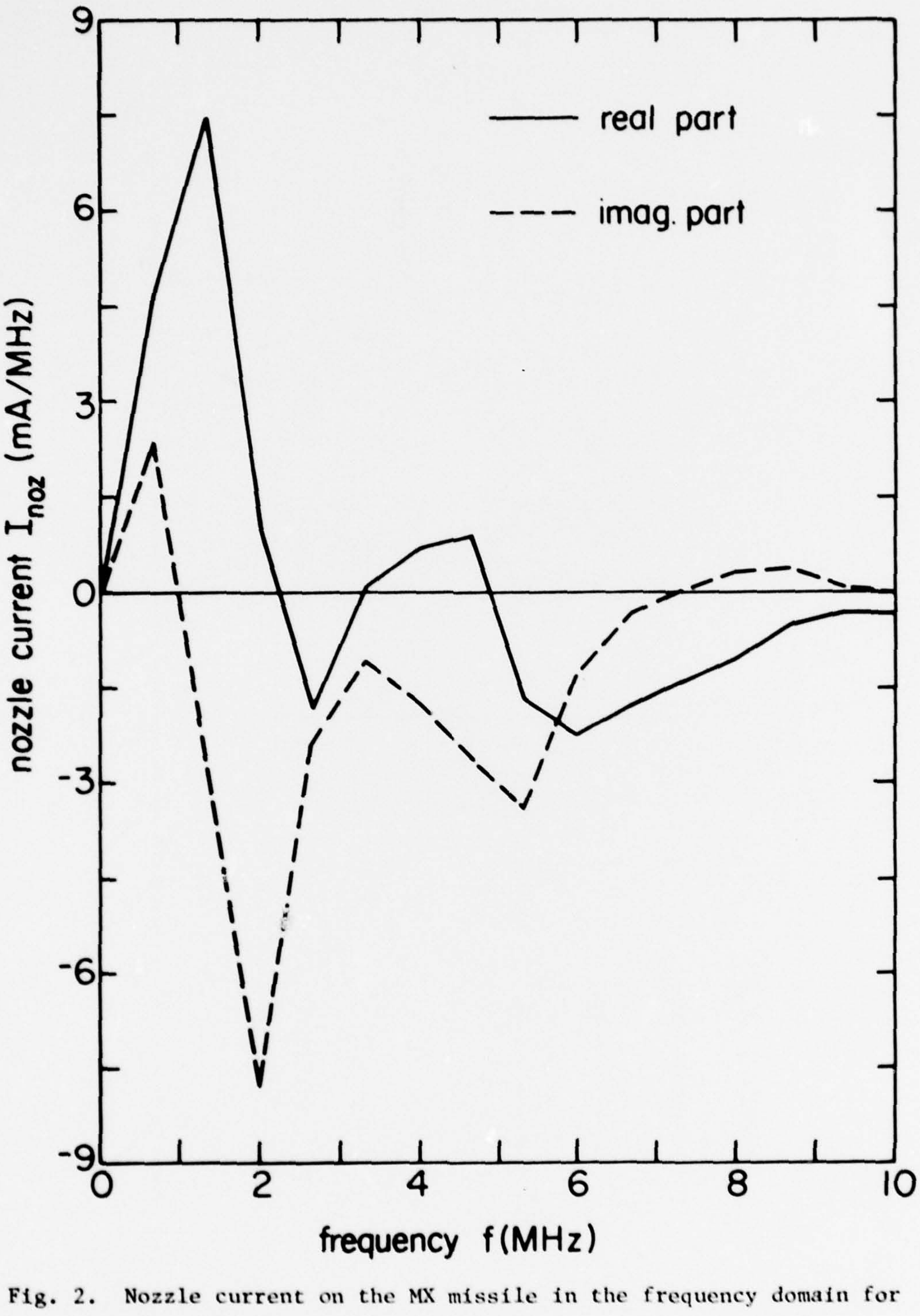

Fig. 2. Nozzle current on the MX missile in the frequency domain for broadside EMP incidence, as calculated in Ref. [1]. The incident electric field is directed along the length of the missile and of intensity 1 volt per meter.

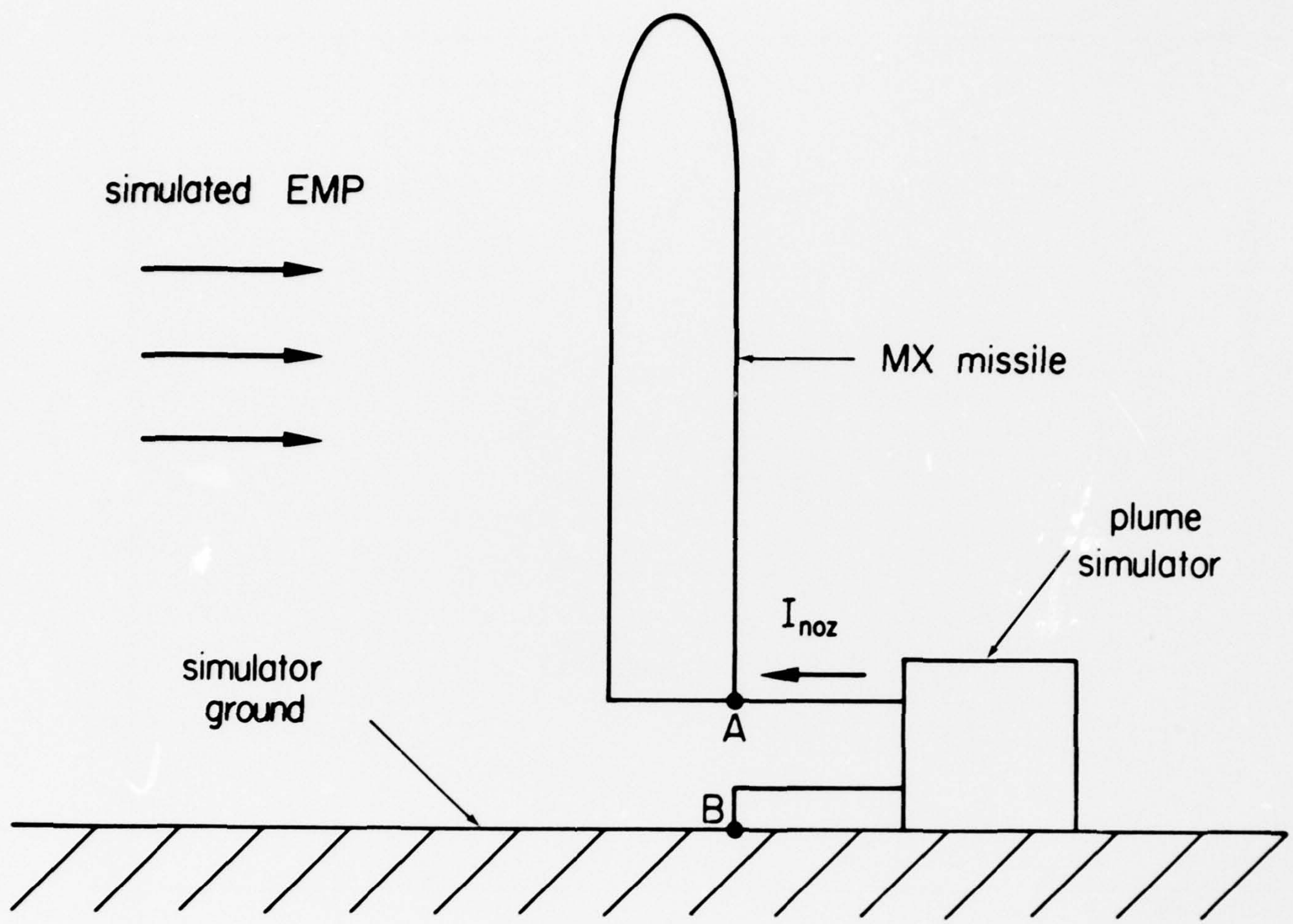

Fig. 3. Geometry of an MX missile under test in an EMP simulator.

However, the same cannot be said of the situation below the nozzle. Instead of the plume, one finds here the missile's image with respect to the simulator ground. Therefore one attempts to compensate for this difference by connecting a plume simulator between the missile nozzle and ground, that is, across the terminals A and B in Fig. 3. This plume simulator is to be so designed as to deliver, in conjunction with the simulator field, a net current to the terminal A equal to the nozzle current I_{noz} induced by the EMP.

The following sections present the parametrization and synthesis of the plume simulator.

II. PARAMETRIZATION OF THE PLUME SIMULATOR

The interaction of the EMP simulator field with the missile sets up electric currents on the missile skin and the simulator ground. As seen at the two terminals A and B in Fig. 3, this electromagnetic excitation of the missile can be described by a Thévenin equivalent circuit shown in Fig. 4. The circuit consists of an open-circuit voltage V_{oc} and an input impedance Z_{in} connected in series.

Under the assumption of a perfectly-conducting simulator ground, the input admittance Y_{in} $(= 1/Z_{in})$ across the terminals A and B has been calculated for the MX missile [1]. The results are plotted in Fig. 5. If the terminals A and B are short-circuited, a short-circuit current I_{sc} will flow from terminal B to terminal A . It is given by

$$I_{sc} = V_{oc}/Z_{in} = Y_{in}V_{oc} \tag{1}$$

This current has been calculated for the case of a broadside incident simulated EMP whose electric field is vertically polarized and at a strength of 1 volt per meter [1]. The results are plotted in Fig. 6.

In a similar fashion the plume simulator of Fig. 3 can be represented by a Thévenin equivalent circuit between the terminals A and B , consisting of an open-circuit voltage V_s and an input impedance Z_s . When the plume simulator is hocked up to the missile during testing, the entire test system consisting of the EMP simulator, the missile and the plume simulator is described by the closed circuit shown in Fig. 7. The plume simulator parameters V_s and Z_s must be so chosen that the current flowing in the circuit -- and hence through the terminal A onto the missile -- is equal to the nozzle current I_{noz} given in Fig. 2.

The circuit in Fig. 7 yields the relation

$$(Z_{in} + Z_s)I_{noz} = V_{oc} + V_s \tag{2}$$

Solving for Z_s , one has

$$Z_s = Z_1 + Z_2 \tag{3}$$

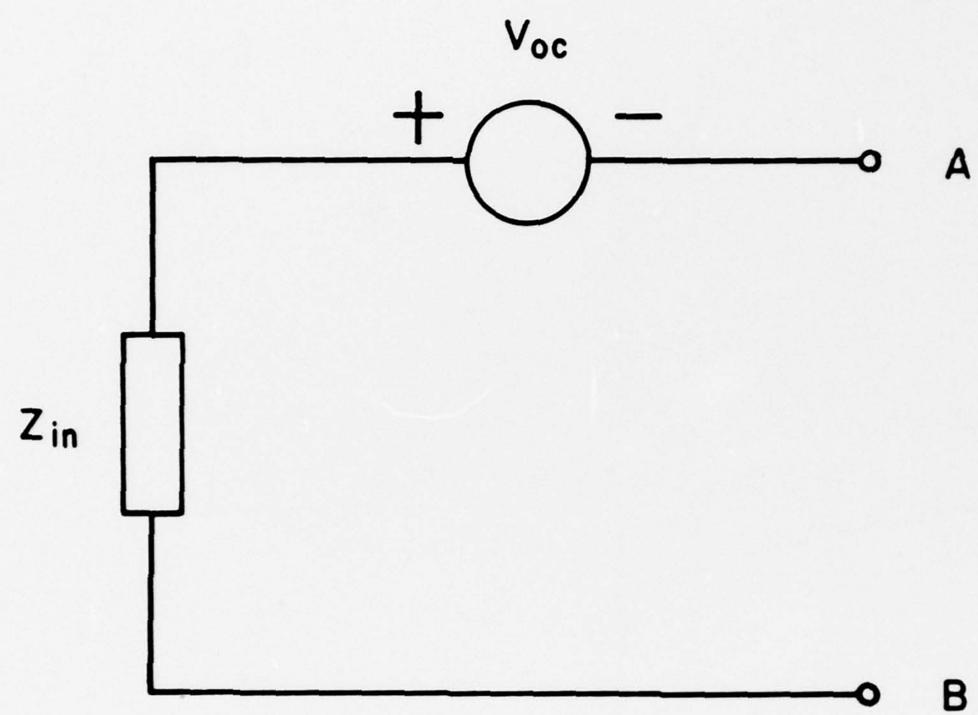

Fig. 4. Thévenin equivalent circuit representing a missile excited by an EMP.

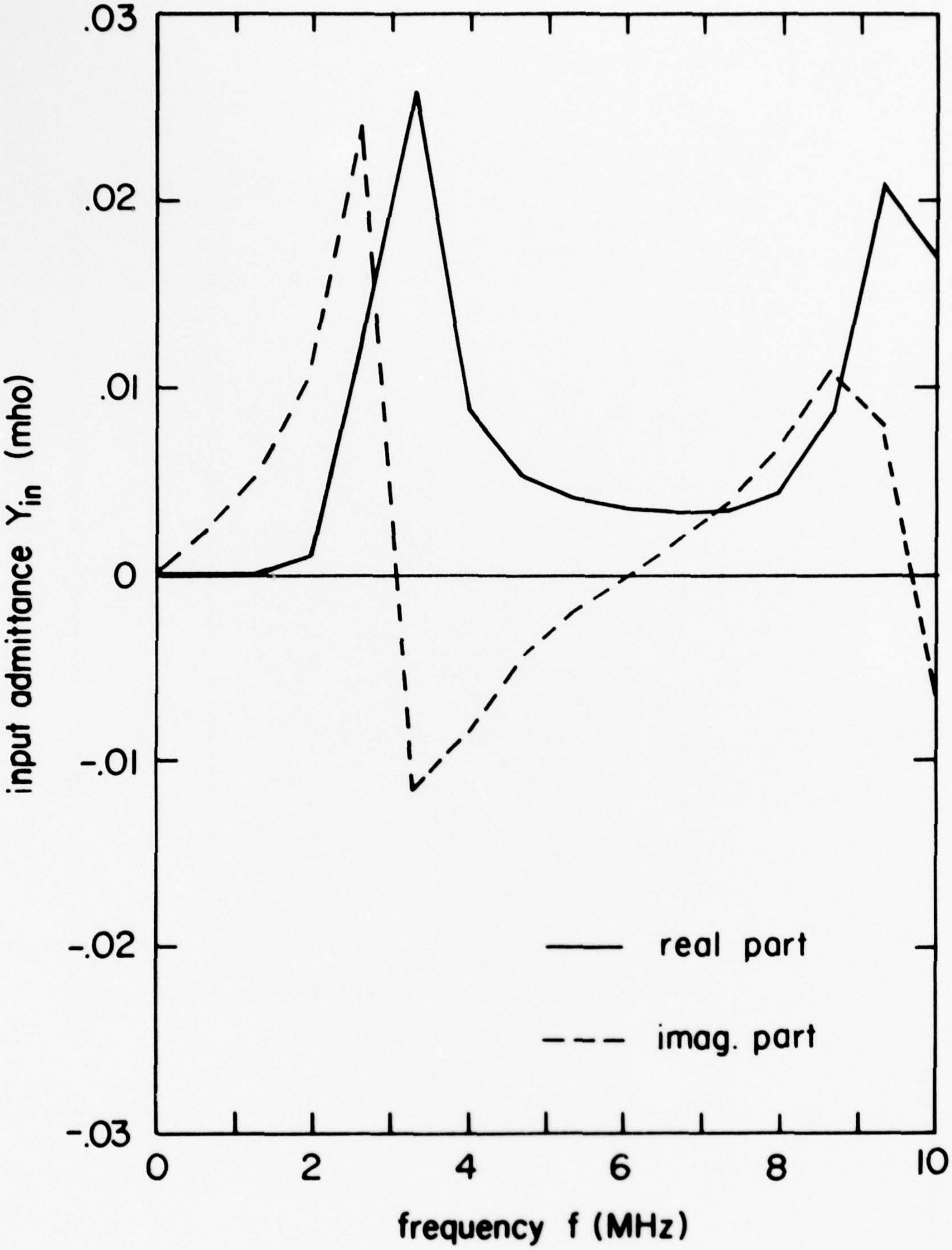

Fig. 5. Input admittance of an upright MX missile relative to a perfectly-conducting ground, as calculated in Ref. [1].

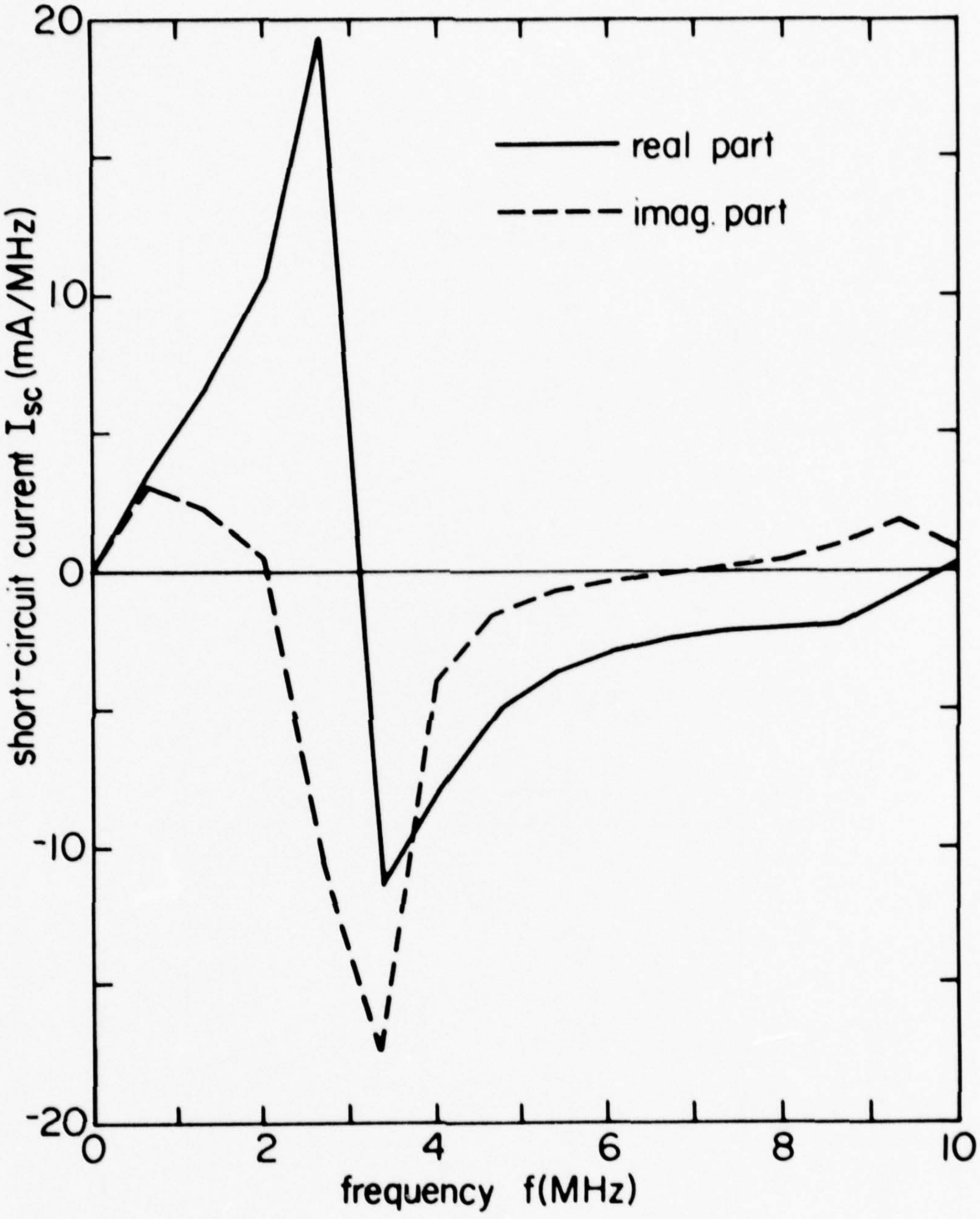

Fig. 6. Short-circuit current flowing from ground to the MX missile nozzle for broadside simulator EMP incidence, as calculated in Ref. [1]. The simulator electric field is vertically polarized and of intensity 1 volt per meter.

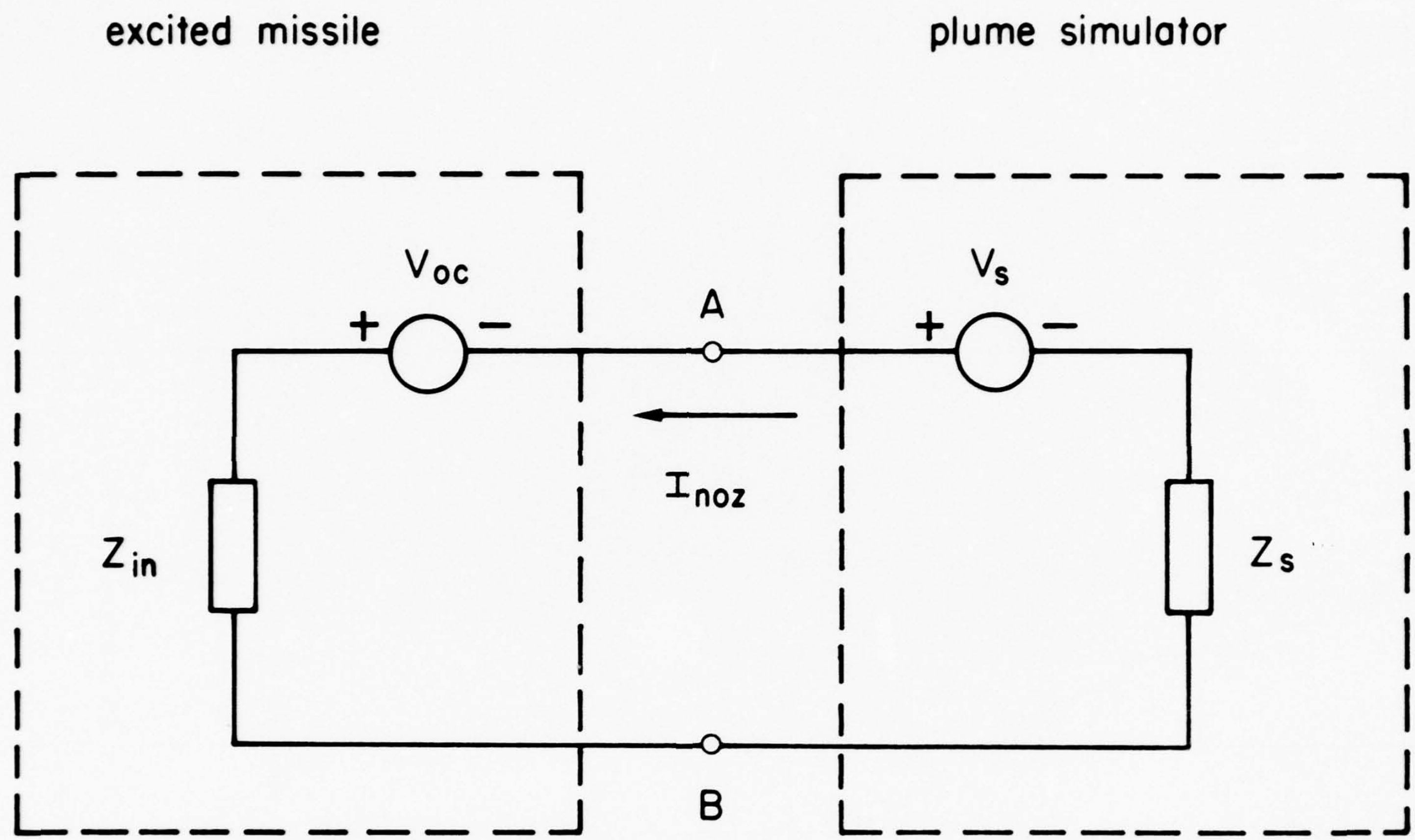

Fig. 7. Equivalent circuit for a missile under test in an EMP simulator and connected to a plume simulator.

where

$$Z_1 = \frac{V_{oc}}{I_{noz}} - Z_{in} = \left(\frac{I_{sc}}{I_{noz}} - 1 \right) Z_{in} \tag{4}$$

and

$$Z_2 = \frac{V_s}{I_{noz}} \tag{5}$$

Z_s is a passive network element. Its real part must satisfy the requirement of being nonnegative.

Consider first Z_1 , or rather its reciprocal the admittance Y_1 :

$$Y_1 = \frac{1}{Z_1} = \frac{Y_{in}}{I_{sc}/I_{noz} - 1} \tag{6}$$

From the values of I_{noz} , Y_{in} and I_{sc} in Figs. 2,5 and 6, one can evaluate Y_1 . The results are shown in Fig. 8. The most noticeable feature of Y_1 is that its real part is practically nonnegative up to nearby 10 MHz , with the negligible exception of a very small dip below 0 between 5 and 6 MHz. How Y_1 behaves above 10 MHz is here immaterial, since the currents I_{noz} and I_{sc} do not have significant components in this high-frequency region.

The fact that the real part of Y_1 is positive in the frequency range of interest has certain far-reaching implications. First, it implies that Y_1 itself can be realized with passive network elements alone. More important, it implies that the active element V_s in the plume simulator equivalent circuit is really redundant. The plume simulator can be made simply out of Y_1 . Only when the real part of Y_1 has large negative values will a nonzero V_s be needed to keep the real part of the overall plume simulator impedance Z_s (= $Z_1 + Z_2$) nonnegative.

One therefore concludes that the MX missile plume simulator need only consist of a 1-port passive network parametrized by the input admittance Y_s (= $1/Z_s$) :

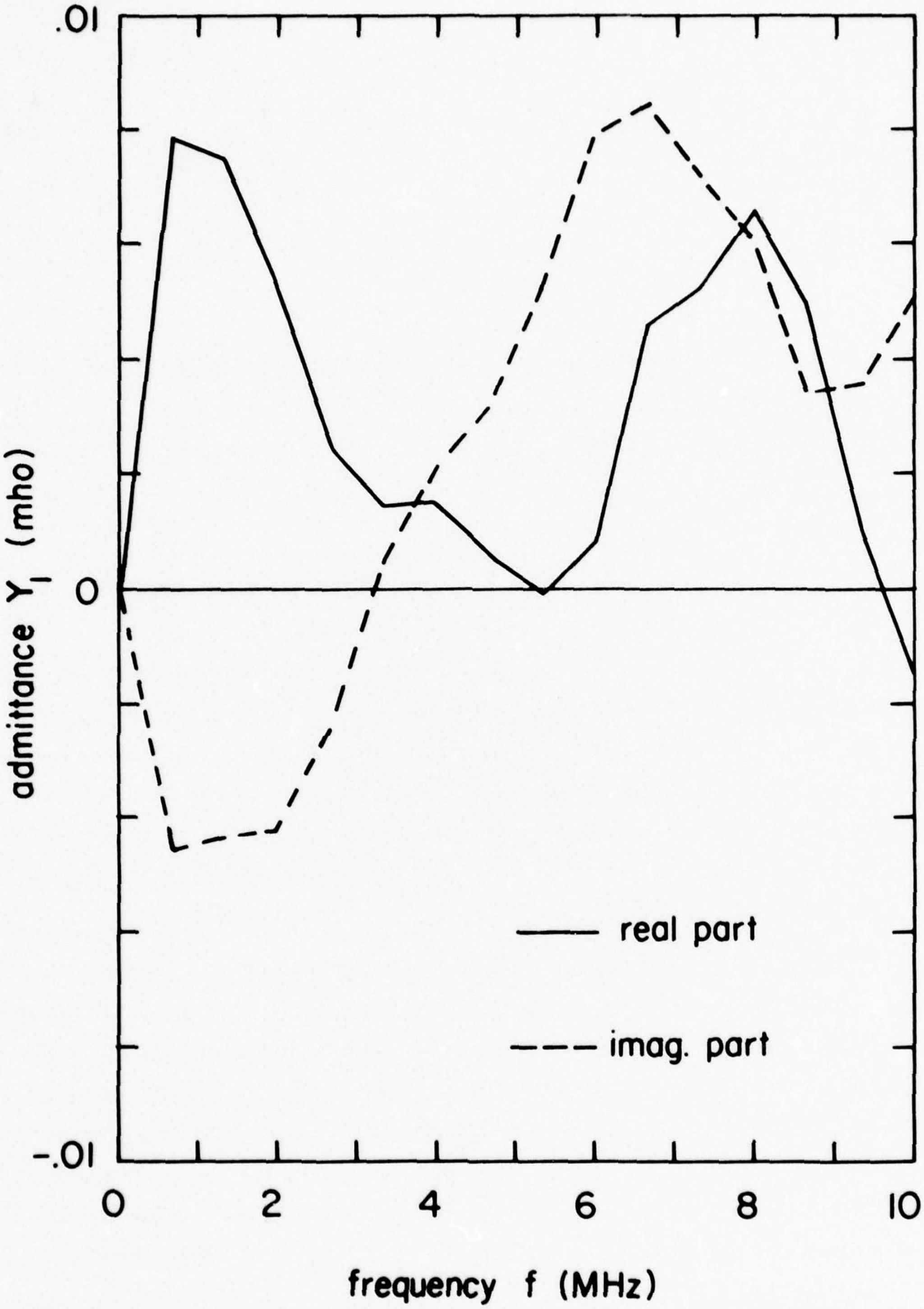

Fig. 8. Admittance Y_1 as a function of frequency f.

$$Y_s = Y_1 = \frac{Y_{in}}{I_{sc}/I_{noz} - 1} \tag{7}$$

The values of this admittance are given in Fig. 8. The voltage source V_s in Fig. 7 can be chosen 0 . This is because the open-circuit voltage V_{oc} due to the EMP simulator field is by itself strong enough to generate the nozzle current I_{noz} in the closed circuit in Fig. 7.

III. SYNTHESIS OF THE PLUME SIMULATOR

One proceeds to synthesize the plume simulator input admittance Y_s defined in Fig. 8, using only lumped LRC elements. The synthesis of the real part is first performed, followed by that of the imaginary part.

Synthesis of Re Y_s

The real part of Y_s in Fig. 8 shows two peaks. It can be realized with the lumped network circuit in Fig. 9, consisting of two resistors R_1 and R_2, two inductors L_1 and L_2, and one capacitor C_2. For this network one has

$$\text{Re } Y_s = \frac{R_1}{R_1^2 + (\omega L_1)^2} + \frac{R_2}{R_2^2 + \left(\omega L_2 - \frac{1}{\omega C_2}\right)^2} \tag{8}$$

with

$$\omega = 2\pi f \tag{9}$$

The values of the network elements are adjusted to fit the locations, widths and heights of the peaks. One finds that

$$R_1 = 100\,\Omega \qquad L_1 = 8\ \mu H \tag{10}$$

and that

$$R_2 = 167\,\Omega \qquad L_2 = 13.3\ \mu H \qquad C_2 = 30\ pF \tag{11}$$

The actual and simulated values of Re Y_s are plotted in Fig. 10 for comparison. One notices a disagreement at very low frequencies. As the frequency f approaches 0, the actual value of Re Y_s approaches 0 while the simulated value approaches a finite limit. This discrepancy, however, is not important, since both the currents I_{noz} and I_{sc} vanish at zero frequency. One can, if one chooses, bring the simulated value of Re Y_s down to 0 at zero frequency by adding a very large capacitor in series with L_1 and R_1.

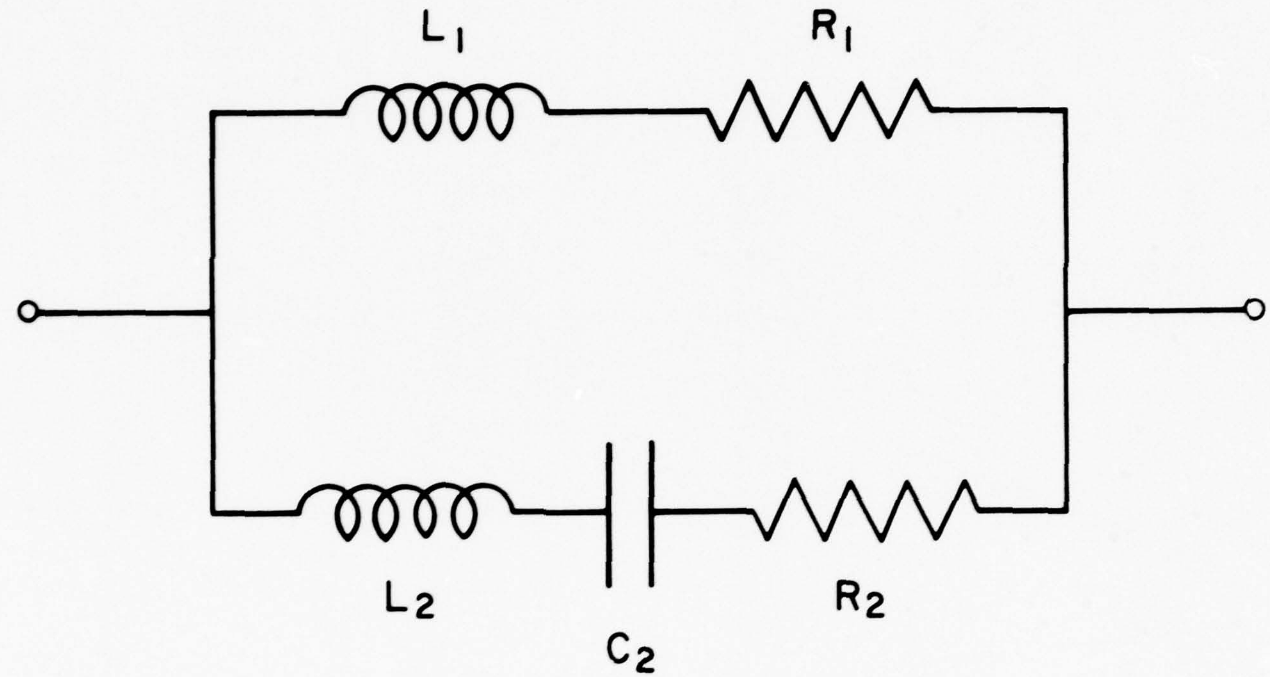

Fig. 9. Network for realizing the real part of the input admittance Y_s of the plume simulator.

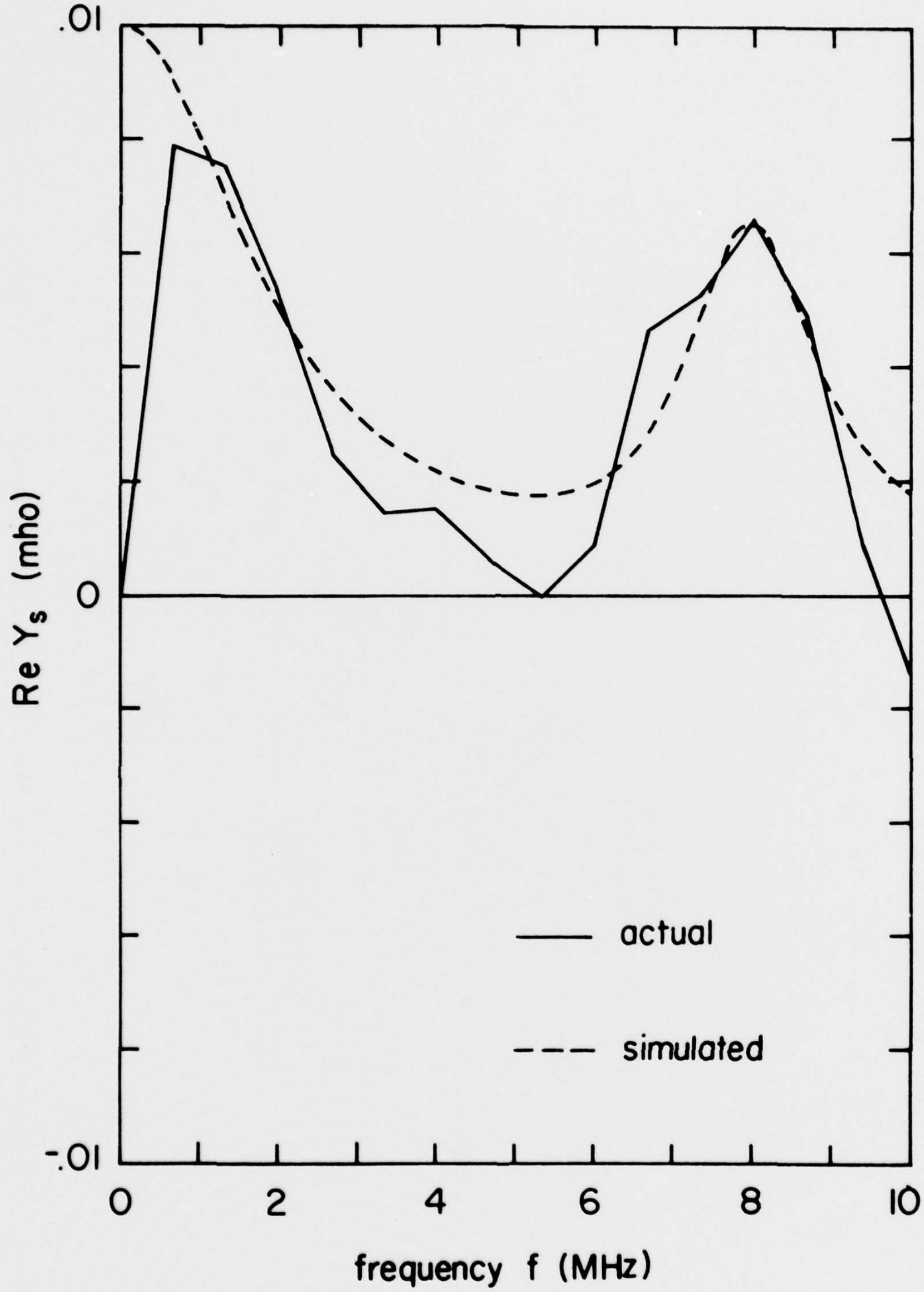

Fig. 10. Comparison between the actual and simulated values of Re Y_s .

Synthesis of $\operatorname{Im} Y_s$

The imaginary part of the input admittance calculated from the network in Fig. 9 does not fit the actual values of $\operatorname{Im} Y_s$ specified in Fig. 8. Nevertheless, it is found possible to synthesize this difference by simply adding to the original network an inductor L_3 and a capacitor C_3 in parallel, as shown in Fig. 11. One then has

$$\operatorname{Im} Y_s = \frac{-\omega L_1}{R_1^2 + (\omega L_1)^2} + \frac{-\left(\omega L_2 - \frac{1}{\omega C_2}\right)}{R_2^2 + \left(\omega L_2 - \frac{1}{\omega C_2}\right)^2} + \omega C_3 - \frac{1}{\omega L_3} \tag{12}$$

The added elements do not affect the real part of Y_s. By choosing the values

$$L_3 = 53\ \mu H \qquad C_3 = 187\ pF \tag{13}$$

one obtains a good fit between the actual and simulated values of $\operatorname{Im} Y_s$ in the most important frequency range between 1 and 3 MHz where the largest current components are found. The results are shown in Fig. 12. Again, the discrepancy at very low frequencies is unimportant.

Simulated Nozzle Current

The express purpose of the plume simulator is to deliver the correct nozzle current I_{noz} to the missile nozzle during EMP simulator testing. With the plume simulator made up of the passive network shown in Fig. 11, the simulated nozzle current is given by

$$I_{noz} = \frac{Y_s}{Y_{in} + Y_s} I_{sc} \tag{14}$$

where Y_{in} is defined by Fig. 5 and I_{sc} by Fig. 6. The plume simulator input admittance Y_s is now given by

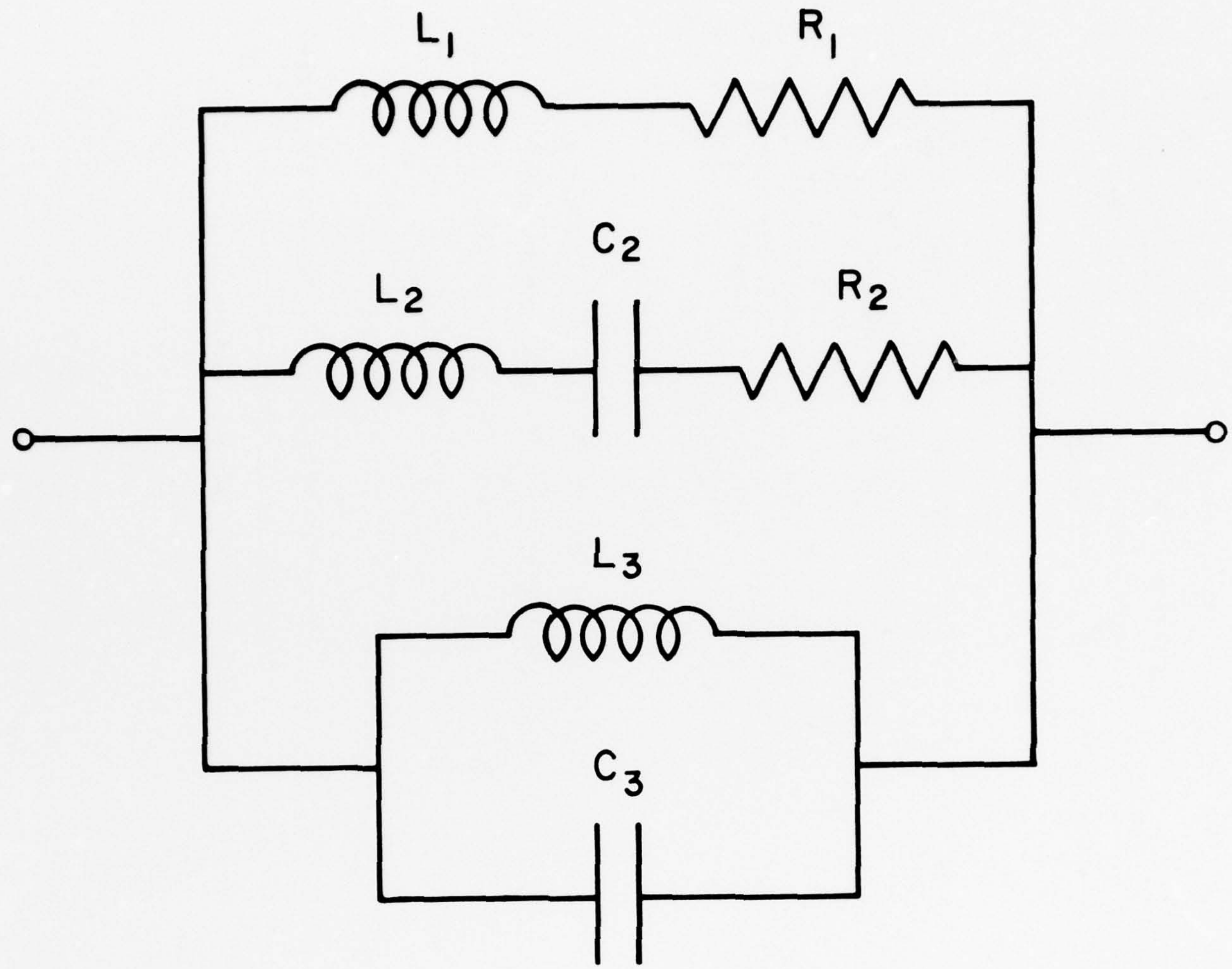

Fig. 11. Network for realizing the imaginary part of the input admittance Y_s of the plume simulator.

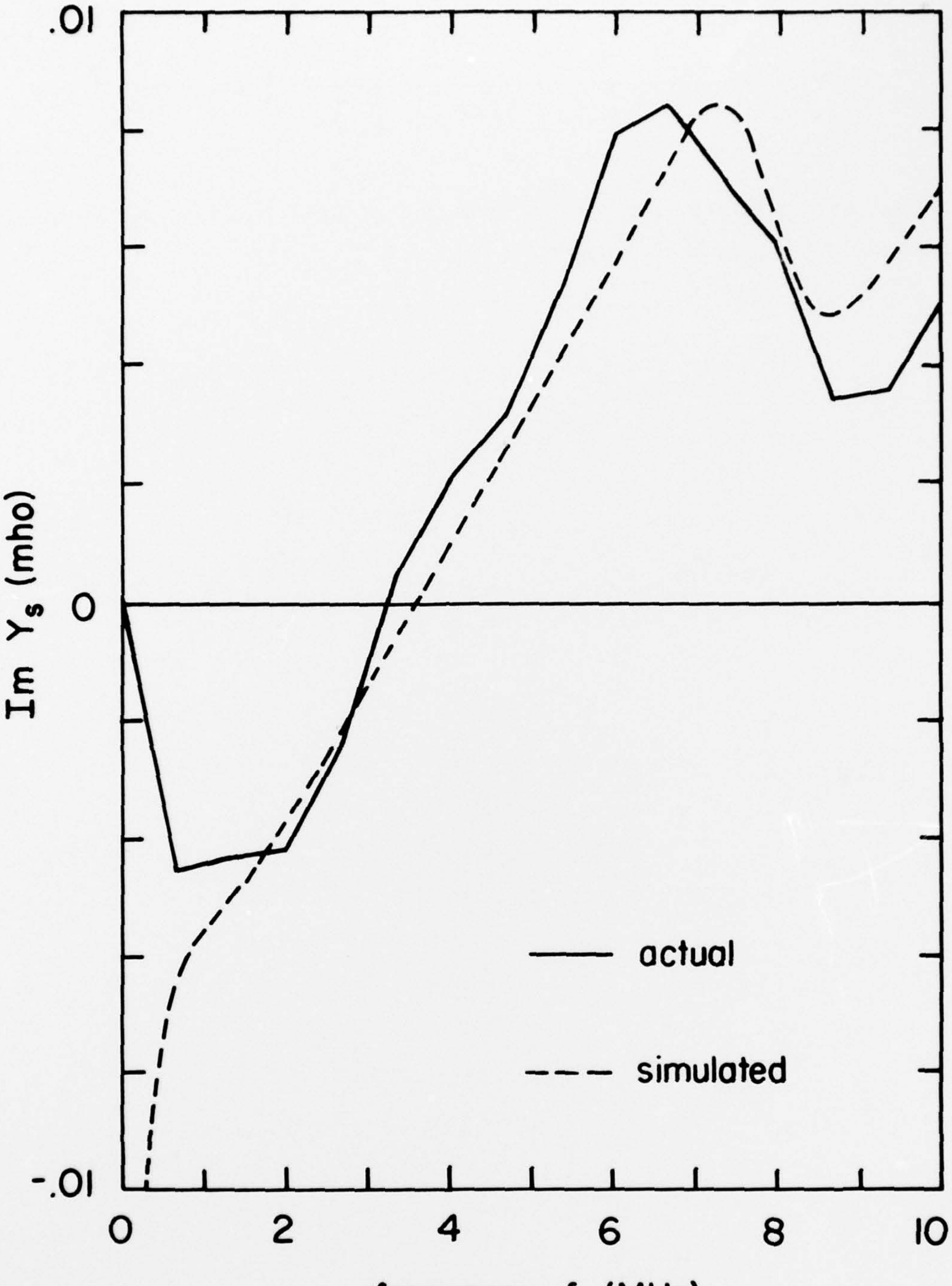

Fig. 12. Comparison between the actual and simulated values of Im Y_S .

$$Y_s = \frac{1}{R_1 + j\omega L_1} + \frac{1}{R_2 + j\left(\omega L_2 - \frac{1}{\omega C_2}\right)} + j\left(\omega C_3 - \frac{1}{\omega L_3}\right) \tag{15}$$

The actual and simulated nozzle currents are plotted in Figs. 13 and 14 for comparison. The agreement is good.

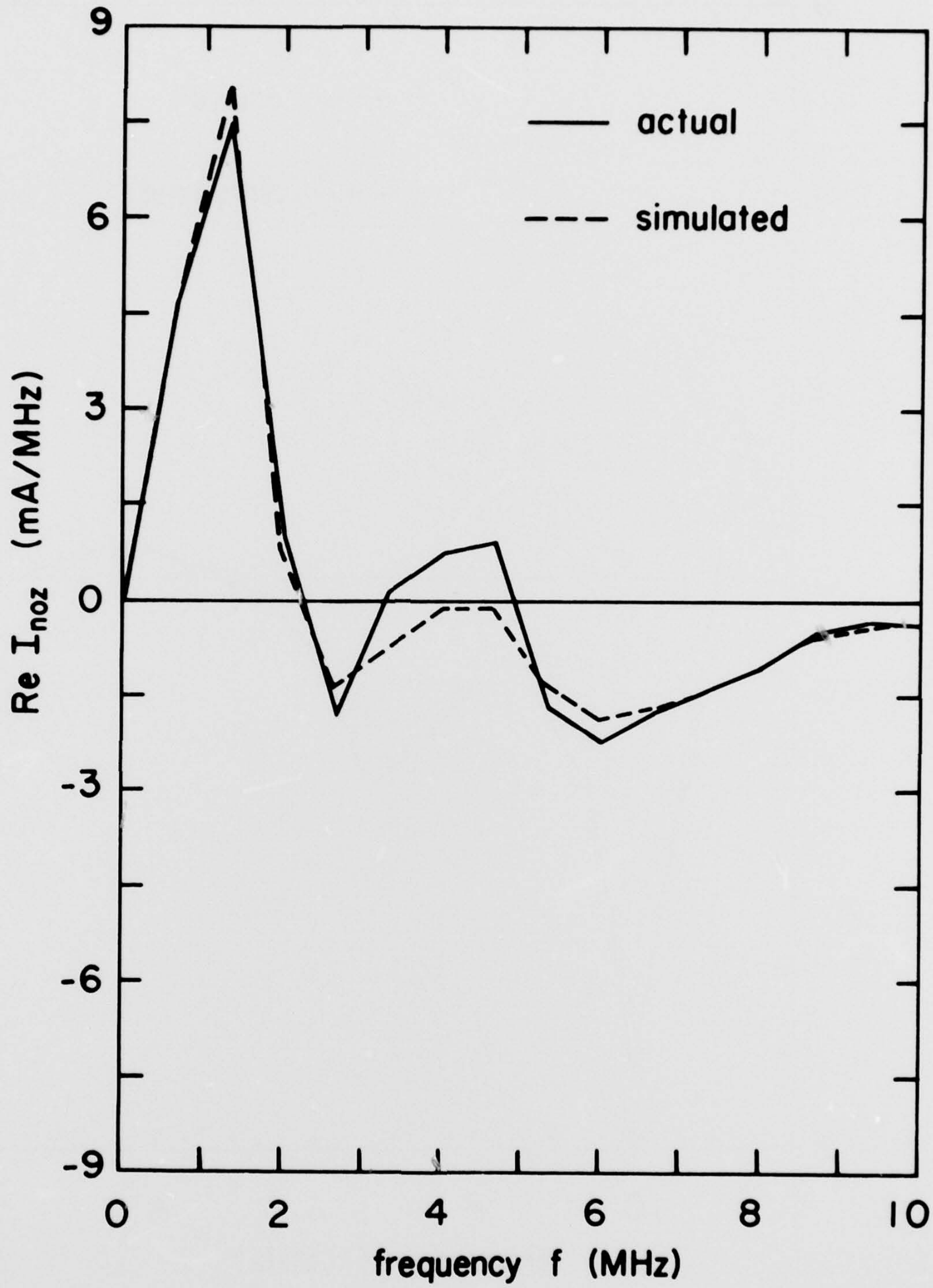

Fig. 13. Comparison between the actual and simulated values of the nozzle current : real part.

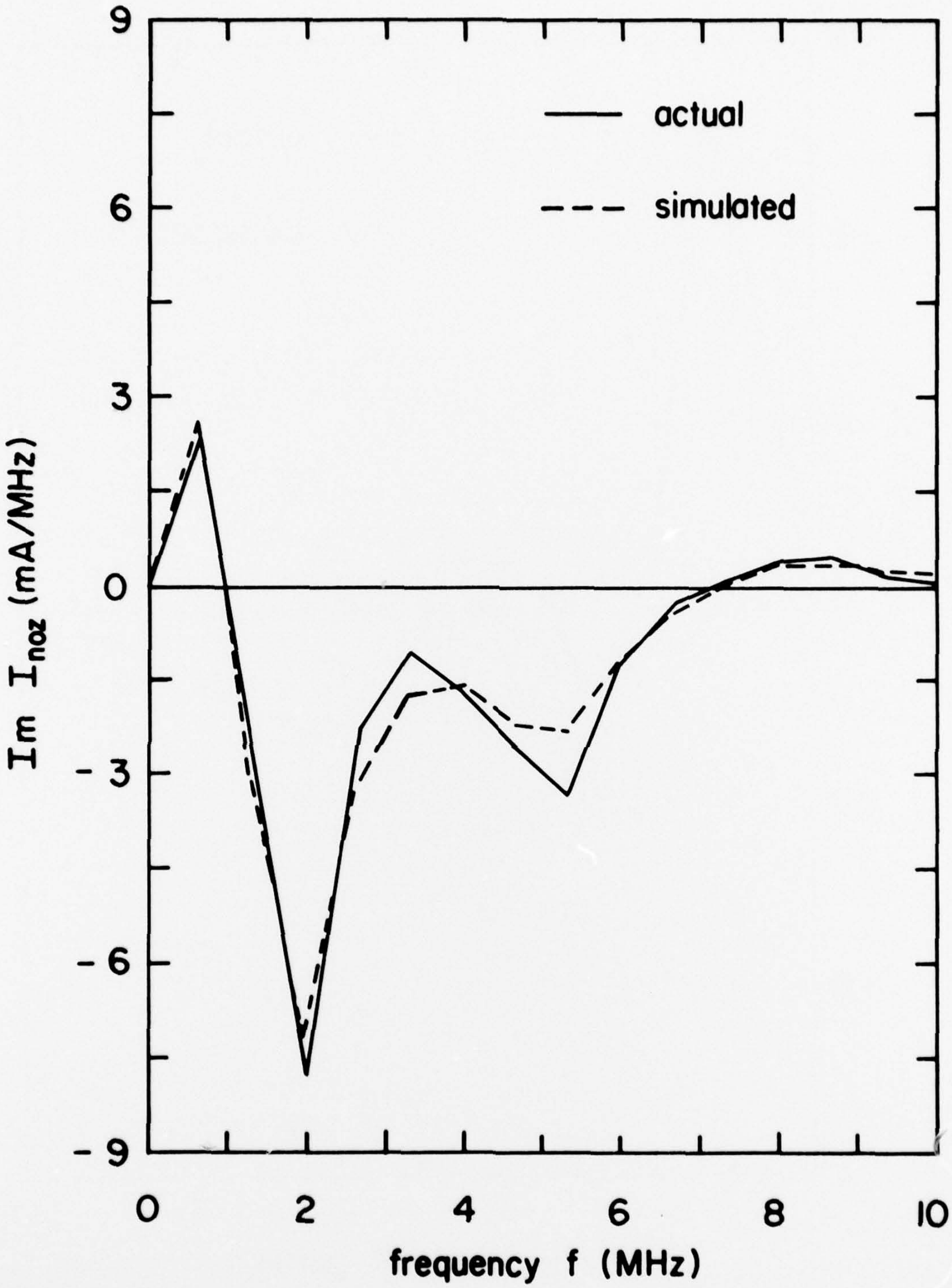

Fig. 14. Comparison between the actual and simulated values of the nozzle current : imaginary part.

IV. CONCLUSIONS

The interaction of an EMP with the exhaust plume of an MX missile and its effects on the missile itself can be simulated during EMP simulator testing by using a plume simulator. The plume simulator is to be connected between the nozzle of the missile and the simulator ground, as shown in Fig. 15a. At EMP frequencies the exact geometry of the connection is immaterial as long as the electrical contact is good. The structure of the plume simulator for a given theoretical model of the plume [1] is determined and shown in Fig. 15b. It consists of a passive lumped network characterized by an input impedance Z_s .

For an incident EMP with an electric field intensity of 1 V/m , the peak value of the current flowing through the plume simulator is estimated to be of order 50 mA and the peak value of the voltage across its terminals of order 10 V . Typically the electric field intensity expected in an EMP is of order 50 kV/m . Therefore the plume simulator should be constructed to withstand a current of order 2500 A and a voltage of order 500,000 V .

The advantages of a plume simulator built entirely out of passive elements are many and easy to grasp. First, there is no need to fabricate and service current or voltage generators such as enormous charged capacitors. Second, the delicate technical problem of synchronizing the switching-on of these current or voltage generators with the launching of the EMP simulator field on the missile is thereby eliminated. Third, the same passive plume simulator can be used for different field-strength settings of the EMP simulator.

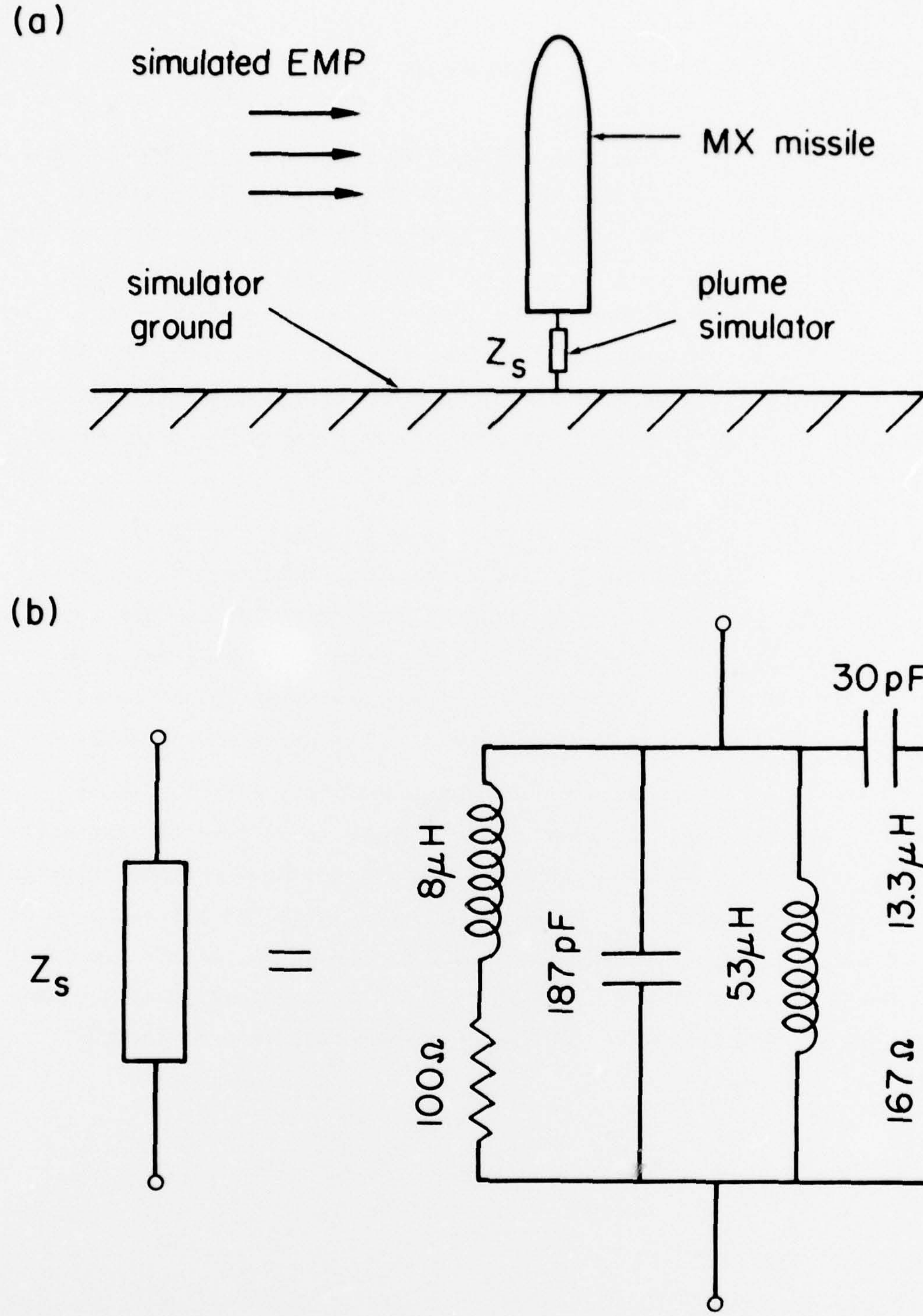

Fig. 15. Structure of a plume simulator for the MX missile.

REFERENCE

[1] Chang, S.K., F.M. Tesche, D.V. Giri, "EMP Coupling to an In-Flight MX Missile in the 0 - 20 Km Altitude Regime", Science Applications, Inc., Berkeley, CA, final report on Contract DNA001-77-C-0184, March 1978.

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ATTN: R. Mortensen
ATTN: Library
ATTN: R. Crolius
ATTN: J. Reinheimer
ATTN: C. Greenhow
ATTN: I. Garfunkel

Battelle Memorial Institute
ATTN: R. Blazek
ATTN: E. Leach

BDM Corp.
ATTN: Corporate Library

BDM Corp.
ATTN: Library

Bendix Corp.
Communication Division
ATTN: Document Control

Bendix Corp.
Research Laboratories Division
ATTN: M. Frank

Bendix Corp.
Navigation and Control Group
ATTN: Dept. 6401

Boeing Co.
ATTN: D. Kemle
ATTN: B. Hanrahan
ATTN: H. Wicklein
ATTN: D. Isbell
ATTN: Kent Technical Library

Booz-Allen and Hamilton, Inc.
ATTN: R. Chrisner
ATTN: Technical Library

Brown Engineering Company, Inc.
ATTN: F. Leonard

Burroughs Corp.
Federal and Special Systems Group
ATTN: A. Mauriello

Calspan Corp.
ATTN: Library

Charles Stark Draper Lab., Inc.
ATTN: TIC MS 74
ATTN: K. Fertig

Cincinnati Electronics Corp.
ATTN: L. Hammond

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

Computer Sciences Corp.
ATTN: R. Briggs

Computer Sciences Corp.
ATTN: A. Schiff
ATTN: R. Dickhaut

Control Data Corp.
ATTN: J. Meehan

Cutler-Hammer, Inc.
AIL Division
ATTN: E. Karpen

Dikewood Industries, Inc.
ATTN: Technical Library
ATTN: L. Davis

Dikewood Industries, Inc.
ATTN: K. Lee
ATTN: L. Marin
ATTN: J. Lam

E-Systems, Inc.
ECI Division
ATTN: R. Frank

E-Systems, Inc.
Greenville Division
ATTN: J. Moore

Effects Technology, Inc.
ATTN: S. Clow

EG&G Washington Analytical Services Center, Inc.
ATTN: C. Giles

Electro-Magnetic Applications, Inc.
ATTN: D. Merewether

Ford Aerospace & Communications Corp.
ATTN: F. Poncelet, Jr.
ATTN: K. Attinger

Ford Aerospace & Communications Corp.
ATTN: Technical Library
ATTN: J. Mattingley

Franklin Institute
ATTN: R. Thompson

General Dynamics Corp.
Electronics Division
ATTN: Research Library

General Dynamics Corp.
Inter-Division Research Library
ATTN: Research Library

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

General Electric Co.
Space Division
Valley Forge Space Center
ATTN: J. Andrews

General Electric Co.
Aerospace Electronics Systems
ATTN: C. Hewison

General Electric Co.
ATTN: Technical Library

General Electric Company—TEMPO
Center for Advanced Studies
ATTN: W. McNamara
ATTN: R. Rutherford
ATTN: DASIAC

General Electric Company—TEMPO
Alexandria Office
ATTN: DASIAC

General Research Corp.
Santa Barbara Division
3 cy ATTN: Technical Information Office

Georgia Institute of Technology
Georgia Tech. Research Institute
ATTN: R. Curry

Georgia Institute of Technology
Office of Contract Administration
ATTN: Rsch. & Security Coordinator for H. Denny

Grumman Aerospace Corp.
ATTN: L-01 35

GTE Sylvania, Inc.
Electronics Systems Grp.-Eastern Div.
ATTN: L. Blaisdell
ATTN: C. Thornhill

GTE Sylvania, Inc.
ATTN: M. Nurefora
ATTN: D. Flood
ATTN: J. Waldron
ATTN: E. Motchok
ATTN: C. Ramsbottom

Hazeltine Corp.
ATTN: M. Waite

Honeywell, Inc.
Avionics Division
ATTN: S&RC Library
ATTN: R. Johnson

Honeywell, Inc.
Avionics Division
ATTN: W. Stewart
ATTN: S. Graff

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

Hughes Aircraft Co.
ATTN: J. Singletary
ATTN: CTDC 6/E110
ATTN: K. Walker

IIT Research Institute
ATTN: J. Bridges
ATTN: I. Mindel

Institute for Defense Analyses
ATTN: Tech. Info. Services

International Tel. & Telegraph Corp.
ATTN: Technical Library
ATTN: A. Richardson

Ion Physics Corp.
ATTN: H. Milde
ATTN: R. Evans

IRT Corp.
ATTN: D. Swift

Jaycor
Santa Barbara Facility
ATTN: W. Radasky

Jaycor
ATTN: R. Stahl
ATTN: E. Wenaas

Jaycor
ATTN: Library

Kaman Sciences Corp.
ATTN: W. Ware
ATTN: J. Lubell
ATTN: W. Rich
ATTN: F. Shelton
ATTN: W. Stark

Lawrence Livermore Laboratory
ATTN: Doc. Con. for Technical Information Dept., Library
ATTN: Doc. Con. for L-156, F. Miller
ATTN: Doc. Con. for L-10, H. Kruger
ATTN: Doc. Con. for L-96, T. Donich
ATTN: Doc. Con. for L-153, D. Meeker

Litton Systems, Inc.
Data Systems Division
ATTN: EMC Gp.
ATTN: M848-61

Litton Systems, Inc.
AMECOM Division
ATTN: J. Skaggs

Lockheed Missiles & Space Co., Inc.
ATTN: H. Thayn
ATTN: B. Kimura
ATTN: M. Bernstein
ATTN: E. Smith
ATTN: S. Taimuty
ATTN: G. Heath
ATTN: L. Rossi

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

Lockheed Missiles and Space Co., Inc.
ATTN: Technical Information Center D/Coll

Los Alamos Scientific Laboratory
ATTN: Doc. Con. for B. Noel
ATTN: Doc. Con. for C. Benton
ATTN: Doc. Con. for J. Malik

Lutech, Inc.
ATTN: F. Tesche

M.I.T. Lincoln Lab.
ATTN: L. Loughlin

Martin Marietta Corp.
Orlando Division
ATTN: M. Griffith

Maxwell Labs, Inc.
ATTN: A. Travelpiece

McDonnell Douglas Corp.
ATTN: T. Ender

McDonnell Douglas Corp.
ATTN: Technical Library Services
ATTN: S. Schneider

Mission Research Corp.
ATTN: W. Hart
ATTN: EMP Group

Mission Research Corp.
EM System Applications Division
ATTN: L. McCormick
ATTN: A. Chodorow

Mission Research Corp.-San Diego
ATTN: V. Van Lint

Mitre Corp.
ATTN: M. Fitzgerald

Norden Systems, Inc.
ATTN: Technical Library

Northrop Corp.
Electronic Division
ATTN: B. Ahlport
ATTN: Rad. Effects Grp.
ATTN: V. Demartino
ATTN: L. Smith

Palisades Inst. for Rsch. Services, Inc.
ATTN: Records Supervisor

Physics International Co.
ATTN: Document Control

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

R & D Associates
ATTN: R. Schaefer
ATTN: M. Grover
ATTN: B. Gage
ATTN: C. MacDonald
ATTN: Document Control
ATTN: C. Mo

R & D Associates
ATTN: J. Bombardt

Raytheon Co.
ATTN: G. Joshi

Raytheon Co.
ATTN: H. Flescher

RCA Corp.
Government Systems Division
Astro Electronics
ATTN: G. Brucker

RCA Corp.
David Sarnoff Research Center
ATTN: L. Minich

RCA Corp.
ATTN: O. Whitehead
ATTN: R. Rostrom

Rockwell International Corp.
ATTN: N. Rudie
ATTN: V. Michel
ATTN: J. Monroe
ATTN: D/243-068, 031-CA31

Rockwell International Corp.
Space Division
ATTN: B. White

Rockwell International Corp.
ATTN: B-1, Div. TIC (BAOB)

Rockwell International Corp.
ATTN: F. Shaw

Sanders Associates, Inc.
ATTN: R. Despathy

Sandia Laboratories
ATTN: Doc. Con. for E. Hartman
ATTN: Doc. Con. for G. Yonas
ATTN: Doc. Con. for T. Martin
ATTN: Doc. Con. for R. Parker
ATTN: Doc. Con. for C. Vittitoe

Science Applications, Inc.
ATTN: R. Parkinson

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

Science Applications, Inc.
Huntsville Division
ATTN: N. Byrn

Science Applications, Inc.
ATTN: W. Chadsey

Singer Co.
ATTN: Security Manager for Technical Information Center

Sperry Rand Corp.
Sperry Microwave Electronics
ATTN: M. Cort

Sperry Rand Corp.
Sperry Division
ATTN: Technical Library

Sperry Rand Corp.
Sperry Flight Systems
ATTN: D. Schow

Spire Corp.
ATTN: R. Little
ATTN: J. Uglum

SRI International
ATTN: A. Whitson
ATTN: G. Carpenter
ATTN: B. Gasten

Systems, Science & Software, Inc.
ATTN: A. Wilson

DEPARTMENT OF DEFENSE CONTRACTORS (Continued)

Texas Instruments, Inc.
ATTN: D. Manus
ATTN: Technical Library

Texas Tech. University
ATTN: T. Simpson

TRW Defense & Space Sys. Group
ATTN: H. Holloway
ATTN: O. Adams
ATTN: W. Gargaro
ATTN: R. Plebuch
ATTN: L. Magnolia

United Technologies Corp.
Hamilton Standard Division
ATTN: Chief, Elec. Design

Varian Associates, Inc.
ATTN: H. Jory

Westinghouse Electric Corp.
Advanced Energy Systems Div.
ATTN: Technical Library